Chapter 3
Climate Change and Global Warming

We have discussed the pieces of the climate system and how they interact through some of the key cycles between parts of the climate system. These cycles include the hydrologic (water) and carbon cycles. In this chapter we describe *why* climate changes, with a brief examination of *how* it changes. Details of potential specific climate changes are discussed in Sect. 3.3. The energy budget of the planet is critical for understanding how the climate system may change over time, because on long timescales, climate is governed largely by the total amount of energy in the system and where it goes. Changes to the energy budget, both natural and caused by humans, will cause *climate change*. Because climate is a set of different distributions of weather states in different places, climate change is the altering of some or all of these distributions (e.g., temperature or rainfall at a particular place). *Global warming* implies a specific metric (global average temperature) and a specific direction (warming or a positive trend). Global warming is a subset of climate change.

In this chapter we start with some basic concepts. We start by showing how changes in climate can happen internally in the climate system as a result of coupling of different processes, and we introduce the concept of a feedback (see box) that alters the response of the climate system in reaction to a change to energy that forces the system. We then talk about how the climate system responds to being "pushed": generally with a change in the external heat added or removed. Greenhouse gases trap more heat in the system; hence, they provide this push, or "forcing." We can see how this has happened over the distant (geologic) past and what is currently happening based on the recent (observed) past. Finally, we investigate how the system responds to changes in the energy flow and where it might put the heat: how the changes to the heat input and output may result in climate changes. These are all basic background points for understanding the underlying premise of climate change and, hence, the goals of a climate model to predict climate changes.

A. Gettelman and R.B. Rood, *Demystifying Climate Models*,
Earth Systems Data and Models 2, DOI 10.1007/978-3-662-48959-8_3

3.1 Coupling of the Pieces

The different components and processes in the climate system are "coupled" together like a complex and three-dimensional jigsaw puzzle. In this context, coupling refers to the two-way interaction between different parts of the climate system. Take, for example, processes regulating water in the hydrologic cycle. Water evaporates from the ocean, leaving salt and changing density, moving through the atmosphere and depositing heat when it condenses and then precipitates onto the terrestrial surface. All these steps couple water and energy together.

The complex **coupling** of the earth system means that it is constantly evolving on many timescales from a day up to millions of years. The daily timescale is driven by earth's rotation. The annual cycle is the earth's orbit around the sun. There may be small fluctuations in the sun over an 11-year solar cycle, or over different solar cycles. The earth's orbit and wobble on its axis takes thousands of years, and over millions of years the continents also rearrange themselves, affecting the components of the system such as the ocean circulation and ice sheets. And of course there are other events that are not cycles: from volcanic eruptions that put gases into the atmosphere and rearrange the surface of the earth, to meteor impacts such as the impact that likely caused the mass extinction when the dinosaurs died out. These events are external climate **forcing**: They exert an external push on the climate system, usually in terms of a change in energy in the system. When we speak of **natural forcing** of the system, it is the changes on these different timescales and how the components of the earth system interact that govern the evolution of climate.

Focus for a moment on the interactions of the various parts of the earth's climate system. Energy comes in through the sun, modulated by the atmosphere, by clouds, and by hitting the surface of the earth. The energy flows through the system (into the land, snow, oceans, and biosphere), and these components respond. The response (change in energy flow) usually has impacts on other parts of the climate system. This we call a **feedback**. (see box).

Feedbacks

Broadly, a feedback occurs when the input is modified by the output of a process. If you have taken a microphone too close to a speaker, you have experienced a **positive feedback**: Sound goes into the microphone, is amplified by the speaker, comes back into the microphone again, is amplified again, and SCREECH! That's a positive feedback loop. In terms of climate science, a feedback is an internal reaction or response of the climate system to external changes (forcing) that results in more changes to the system (enhanced or reduced forcing).

A positive feedback amplifies a signal. That can mean that changes get larger in either direction. With climate, that means a positive feedback amplifies a change regardless of direction. Think of the example of a snow-covered surface. Being white, it reflects away most of the sunlight. If it warms up and melts, the darker surface beneath absorbs more energy and warms more. This is a positive feedback. It tends to reinforce a small change: Warming melts snow, which melts more snow and causes more warming. But, if there is a cooling that creates more snow, this causes more cooling and more snow. So a positive feedback pushes the system away from its original state: It is destabilizing. This is critical to understand. A positive feedback enhances changes in the direction they start: It enhances warming, but it also enhances cooling. One analogy is the effect of gravity at the top of a hill. If you push a ball forward from the top of a hill, it rolls forward down the hill; if you push a ball backward from the top, it rolls backward down the hill. This is an "unstable" situation, and gravity will accelerate any motion downward: it acts in the same way as the motion.

There are also feedbacks that act to resist changes. This is called a **negative feedback**. A negative feedback tends to push the system back to its original state: a stabilizing force. Note that the connotation is the opposite of typical usage in the context of climate change: negative feedbacks stabilize the climate system (which is usually a good thing), whereas positive feedbacks destabilize it. An example of a negative feedback is the "temperature" feedback: A warmer planet radiates more energy to space, which will reduce the tendency of the surface to warm. To continue the analogy with rolling objects, if you are at the bottom of a valley and push a ball forward (uphill), it rolls backward (down) to where it started. If you push a ball backward (also uphill), it rolls forward to where it started. In this situation of a "valley," gravity acts as a negative feedback or stabilizing force: It acts against the motion. We discuss these feedbacks when we discuss the atmosphere in Chap. 5.

Feedbacks are also important in understanding the climate system.[1] Feedbacks govern the sensitivity of climate to changes (also called climate sensitivity). If we change CO_2 (or more specifically the overall radiative forcing from CO_2 and other gases), how much energy will remain in the earth system? Feedbacks "amplify" (or dampen) radiative forcing, resulting in more or less forcing of the system. If CO_2 increases the energy in the system (and the temperature), this might melt more snow and the darker surface increases the energy in the system by decreasing the albedo (more absorption). This is a positive feedback, which increases the sensitivity of the climate system to changes in the **energy budget**, the amount of energy in the earth system. Changes to the energy budget are of fundamental importance because the overall "level" of energy in the system governs the expected average temperature at the surface. An overall energy change implies, "shifts" in the distribution function of climate (refer back to Fig. 1.3), and the sensitivity tells us the degree of shift for a

[1]See Stocker T. S., et al. (2001). "Physical Climate Processes and Feedbacks." In Houghton, J. T., Ding, Y., Griggs, D. J., et al. (eds). *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

given amount of forcing from CO_2 and other gases. So it becomes a useful metric (measure) of where the system might be heading.

We cover feedbacks in more detail when discussing the specific components of the climate system and how we model them in Sect. 3.2. As described in the box, there are both positive feedbacks (like the ice-albedo feedback) and negative feedbacks (like the temperature feedback) in the climate system.

Put a lot of complex feedbacks together, and the climate system starts to sound less like the single screech of an electronic microphone and more like the complex tones of a symphony, perhaps one without a conductor. Many of these tones or combinations of tones have feedback loops, like the example of the sea ice–albedo feedback described here. We discuss this feedback more in Chap. 5, after we introduce additional concepts about how the atmosphere works.

To understand the climate system and how it will evolve over time, it is critical to understand these complex interactions. Most climate science is dedicated to understanding the components of the system, their coupling, and how they work now and have worked in the past, so that we can understand how they might work in the future. The imperative to understand the climate system stems solely from how society is affected by variations in high-frequency extreme weather events and lower frequency climate extremes and how they may change over time in response to different forcings within the system. Or even with no forcing of the system. The importance of understanding weather and climate is independent of any human influence. Even if we did not have reason to think the climate was changing due to human activities, it would still be important and critical to understand and simulate the climate system to predict the natural variability and potential changes in the system so that we can adjust. This is also called adaptation to climate changes, as in adapting our society to a new climate.

3.2 Forcing the Climate System

The **anthroposphere**, the range of human activity, now exerts a strong effect on the climate system. The change in greenhouse gases caused by human activity changes the energy flow in the climate system and creates a forcing on the system. Humans, though largely terrestrial creatures (except for our boats, surfboards, and air travel) are a significant part of the climate system. It is not from the carbon in our bodies. We are small fish, really, compared to all the fish, or rather plankton, in the sea. Our impact comes instead from the carbon from dead plant and animal material that we use as energy. **Fossil fuels** (coal, oil, and gas) are buried sediments of carbon that we pull out of the ground and break apart by oxidizing them at high temperatures. We break carbon bonds in C–H (and C–H–O) compounds, adding oxygen from the air, and get energy, heat, and the chemical by-products: gaseous CO_2 and water (H_2O). There is nitrogen, too, but we consider that later.

Over the last 200 years, accelerating energy use and industrialization has led to the build-up of CO_2 in the atmosphere. We have observed this in a number of ways.

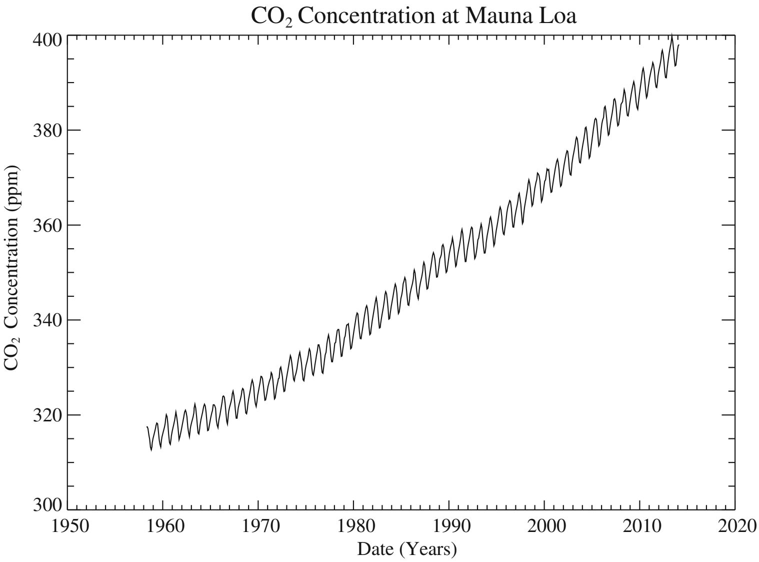

Fig. 3.1 Atmospheric CO_2 concentration from Mauna Loa, Hawaii, in parts per million (ppm) as a function of time

The most direct is through measurements of the concentration of CO_2 in the atmosphere since the 1950s. Every month for 60 years or so, a sample of air is taken and analyzed. Since CO_2 is well mixed in the atmosphere, it represents a broad region (the Northern Hemisphere). Now there are many samples at different stations and multiple instruments, but the answer is the same. The curve in Fig. 3.1 shows two things. One is the upward march of CO_2 concentration over time. The other is the annual cycle of the earth's biosphere: There is an annual cycle in atmospheric CO_2 concentration that occurs because plants in the Northern Hemisphere grow in the spring and turn CO_2 into plant material (leaves, for example), drawing down the concentration. In the autumn, leaves fall and decompose, and much of the carbon returns to the atmosphere. But upward the concentration goes. The curve in the figure is iconic enough to be named the Keeling Curve after the American scientist, Charles Keeling, who first started the measurements in 1958 and made the plot.[2] The units are in parts per million, which means one molecule of CO_2 for every one million molecules of air.

Some observers like to compare this annual cycle of respiration of the whole biosphere (the sum of life on the planet) to the "breathing" of the planet: equating the earth to a single living being. This is an element of the **Gaia hypothesis** put

[2]For a history of the Keeling curve mixed in with the science of climate (and then some policy), see Howe, J. P. (2014). *Behind the Curve: Science and the Politics of Global Warming*. Seattle, WA: University of Washington Press.

forward by James Lovelock and Lynn Margulis in the 1970s.[3] It makes an interesting and powerful analogy that, like a living thing, the earth and its biosphere (the living sphere) interact to make the whole planet itself seem to act like an organism. It is also wonderful to note that the biosphere is so entwined with our planet's climate system that its "breathing" changes the atmosphere. This is another way that life changes the composition of the atmosphere (the oxygen itself is there because of life as well). And it shows the importance of life to the cycle of CO_2 in air.

Now let's talk about the increase over time (the trend), the second important part of Fig. 3.1. There is a steady increase of CO_2 in the atmosphere. This is the result of human emissions of greenhouse gases. It follows fairly closely with the total amount of fossil fuel combustion (burning) estimated over the last few hundred years, starting with the industrial revolution.

We have many lines of evidence that indicate the upward march of CO_2 concentrations is due to human activity. One way is through a direct measurement of the type of carbon present in the atmosphere as CO_2. Different types of the same element are called **isotopes**,[4] with different numbers of neutrons in their atomic nucleus (see box on carbon isotopes). This means they have slightly different mass. And the relative amounts of the different isotopes of carbon atoms in the atmosphere are looking more like the carbon isotopes in fossil fuels. Plant tissue has a slightly different balance of carbon isotopes (see box), and the atmosphere is becoming more abundant in this isotope. This indicates the combustion of dead plant material from fossil fuels. If the fossil fuels were not causing the increase, we would not see changes to the carbon isotopes.

Carbon Isotopes

The standard form (isotope) of carbon has 6 protons and 6 neutrons (^{12}C). In chemical nomenclature, a preceding superscript number on the element (C) indicates the total number of protons and neutrons. The form resulting from cosmic rays hitting CO_2 in the atmosphere has 6 protons and 8 neutrons (^{14}C). ^{14}C is used to carbon date archaeological finds. The atmosphere is starting to have less of a stable form of carbon that has 6 protons and 7 neutrons (^{13}C). ^{13}C occurs differently in the atmosphere than in plant tissues, and the proportion of ^{13}C in the atmosphere is of the right proportion as dead (and fossilized) plant material in fossil fuels.

[3]The original paper on the Gaia hypothesis is Lovelock, J. E., & Margulis, L. (1974). "Atmospheric Homeostasis by and for the Biosphere: The Gaia Hypothesis." *Tellus Series A* (Stockholm: International Meteorological Institute), *26*(1–2): 2–10. There are some good later books by James Lovelock, including, Lovelock, J. (1988). *The Ages of Gaia: A Biography of Our Living Earth*. New York: Norton; and Lovelock, J. (2009). *The Vanishing Face of Gaia*. New York: Basic Books.

[4]For a background on isotopes in the environment, see Michener, R., & Lajtha, K. (2008). *Stable Isotopes in Ecology and Environmental Science*. New York: Wiley.

3.3 Climate History

In addition to direct observations of the atmosphere for the past 50 years, there exist “fossilized” pockets of the atmosphere: samples of air trapped in ice sheets. Direct measurements of air trapped in ice go back all the way to the formation of the glaciers in Antarctica: nearly 800,000 years of CO_2 measurements. The time is measured first by accumulation of layers of ice, then by dating trace elements that decay in the ice or air bubbles, or counting layers. Figure 3.2 illustrates this record from the Vostok station ice core in Antarctica. Two curves are shown. The first is CO_2 concentrations from bubbles in the ice. Notice how it goes up and down. The times when CO_2 is low correspond to ice ages. At 10,000 years ago, the CO_2 concentration rises and the last ice age ends. Why the cycles? They correspond roughly to some of the changes in the earth’s orbit. When conditions favor colder Northern Hemisphere land temperatures, snow sticks around in the summer and ice sheets grow on northern continents. These conditions occur with shifts in the earth’s orbit: changes to the tilt of the earth’s axis so that a larger tilt gives more severe winters in the Northern Hemisphere, or a shift in orbit so that the earth is farther from the sun during the Northern Hemisphere winter. These cycles are called Milankovitch cycles,[5] after Milutin Milanković, a Serbian geophysicist of the early 20th century. These cycles provide a way of understanding past (and future) variations in the earth’s orbit and estimates of the change in solar input (**insolation**) that results. The change in insolation is a natural forcing.

The **ice core record** also contains some interesting signatures in the ice itself.[6] The oxygen in the ice (H_2O) also has isotopes. The forms with more neutrons are “heavier” (^{18}O versus ^{16}O). The heavier form of water tends to remain in liquid phases when water evaporates at the ocean surface, and the relative amounts of heavy and light oxygen in ice thus give a rough measure of the ocean temperature when the ice was deposited. It is not a pure “thermometer” but a relative one, and we can guess at the scale. So oxygen isotopes are used to determine an approximate thermometer and the temperature scale on the right side of Fig. 3.2 is derived from these isotopes (there were no thermometers half a million years ago). The oxygen isotope record is a **proxy** record of temperature.

The story told in the ice is remarkable: The temperature seems to vary in lock step (highly correlated) with the CO_2. When there is more CO_2 (trapping more heat), the temperature is warmer. When there is less CO_2 (less heat trapping), the temperature is colder. We have not said whether the carbon causes the temperature to change or the temperature changes the carbon.

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[5]For more details on paleo-climate, see Hays, J. D., Imbrie, J., & Shackleton, N. J. (1976). “Variations in the Earth’s Orbit: Pacemaker of the Ice Ages,” *Science, 194*(4270): 1121–1132.

[6]For background and details of ice core science, a good review is Alley, R. B. (2000). “Ice-Core Evidence of Abrupt Climate Changes.” *Proceedings of the National Academy of Sciences*, *97*(4): 1331–1334. doi:10.1073/pnas.97.4.1331.

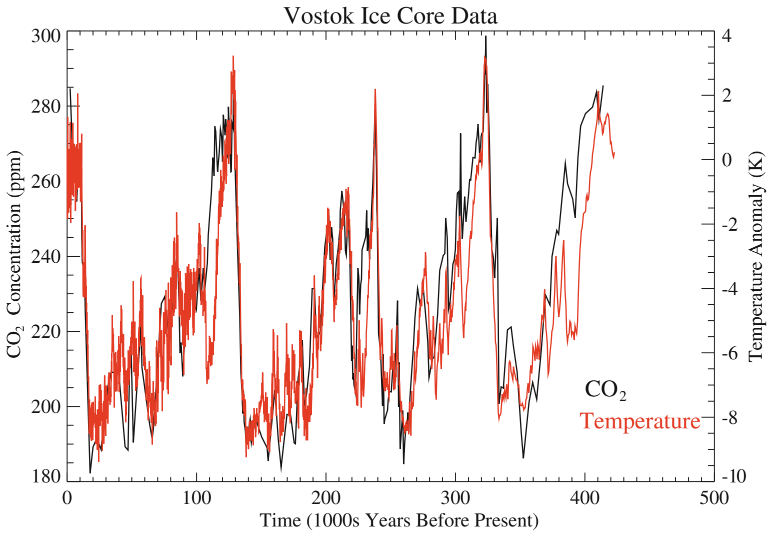

Fig. 3.2 Vostok ice core data. Proxy temperature (from oxygen isotope ratios) in *red* (*right scale*) and CO_2 concentration of air bubbles in *black* (*left scale*). Data from NOAA paleoclimatology program. Petit, J. R., et al. *Vostok Ice Core Data for 420,000 Years*. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series #2001-076. NOAA/NGDC Paleoclimatology Program, Boulder, CO

One of the major complexities of the climate system and climate change is that the "problem" or "pollutant" we are discussing (CO_2) is not something "foreign" to the system. It is a part of the system, a critical part that is naturally all around us. We drink CO_2 (in carbonated drinks and beer, for example), we exhale it, and are bodies are made up of carbon. Carbon is absorbed by plants with photosynthesis and used to build their tissues. This creates the natural annual cycle in Fig. 3.1 of carbon in air. So CO_2 is not bad; it is a natural part of the system. The breathing is natural, but the increase is not.

Thus we have direct records of CO_2 in the atmosphere and evidence that recent changes are caused by humans. This is a strong forcing on the system. We also have evidence through proxy records that temperature has been correlated with CO_2. So we know that in the past the earth's climate has changed with CO_2. To link the change in energy (forcing) with the changes in temperature, we need to understand where the energy goes in the climate system. Climate models are one tool for that, but we can discuss the energy flow in more detail.

3.4 Understanding Where the Energy Goes

As discussed in Chap. 2. The earth radiates away energy to space. Greenhouse gases trap some of this energy that would be radiated away. Higher levels of greenhouse gases mean a small fraction of the energy that used to escape stays in the system. Understanding where the energy goes is critical for understanding how the climate might change over time. The energy has to go somewhere. It can start by evaporating water, for example, but this energy will be released as heat when the water condenses. The energy might heat ocean water, and this water might sink away from the surface of the earth (though it is harder for warmer water to sink). It might be radiated back to space somehow. Or it might go to heat up part of the earth system eventually. The challenge is to use what we know about the system to figure out where the energy goes. All of these possibilities imply some change in "climate" somewhere, even if there is no mean temperature change.

The increase in CO_2 in the atmosphere adds more heat to the system. But we are changing the system by only a small amount. Notice that the vertical axis on Fig. 3.1 does not start at zero. Why should that matter? The complexity with understanding climate change is that we are adding a tiny bit of energy to this wonderfully complex system. What is going to happen?

Perhaps the best analogy for adding CO_2 to the climate system is an analogy with our bodies. CO_2 is like a steroid,[7] a natural substance in our bodies that helps our muscles function. Add a bit more, though, and it throws the system out of balance. Steroids enhance muscle performance in the short term (they may also cause long-term damage), enhancing athletic performances. It only takes a small amount of additional steroid to significantly affect athletic performance. The analogy can be taken one step further. How do you know that any single athletic performance was enhanced by an added steroid? A particular basket in basketball, a hit in baseball, a goal in European football (soccer for those in the United States) depends on a lot, not just the steroids in an athlete's body. And the natural steroids vary as well. So it is hard to say that a single home run in baseball, a single goal, or a single time for a distance runner or cyclist, for example, is due to altered performance. But now look at the distribution of that event over time (number of home runs in a season, average time in a race) and the distribution may have changed (more home runs over a season, for example). So it goes with adding carbon to the system and shifting the distribution of climate events (hurricanes are the tropical thunderstorm equivalent of a home run or a goal). This is how we statistically try to ferret out climate change from all the statistical "noise" of weather events.

Returning to the concept of climate as a distribution introduced in Chap. 1, climate change is the change in that distribution. This is illustrated graphically in Fig. 3.3 (a reprint of Fig. 1.3). We often discuss climate as either the average (or **mean**, where the area is equal on either side) or the **mode** (the most frequent occurrence in the distribution).[8] But as we said earlier, no one ever gets killed by the global average temperature. Nor is anyone killed by mean temperature or

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[7]The analogy between CO_2 and a steroid is usually credited to Jeff Masters and Anthony Broccoli. There is a good video description at https://www2.ucar.edu/atmosnews/attribution/steroids-baseball-climate-change.

[8]Don't be scared by the statistics. See Devore, J. L. (2011). *Probability and Statistics for Engineering and the Sciences*, 8th ed. Duxbury, MA: Duxbury Press, or the terms can be looked up specifically in Wikipedia.

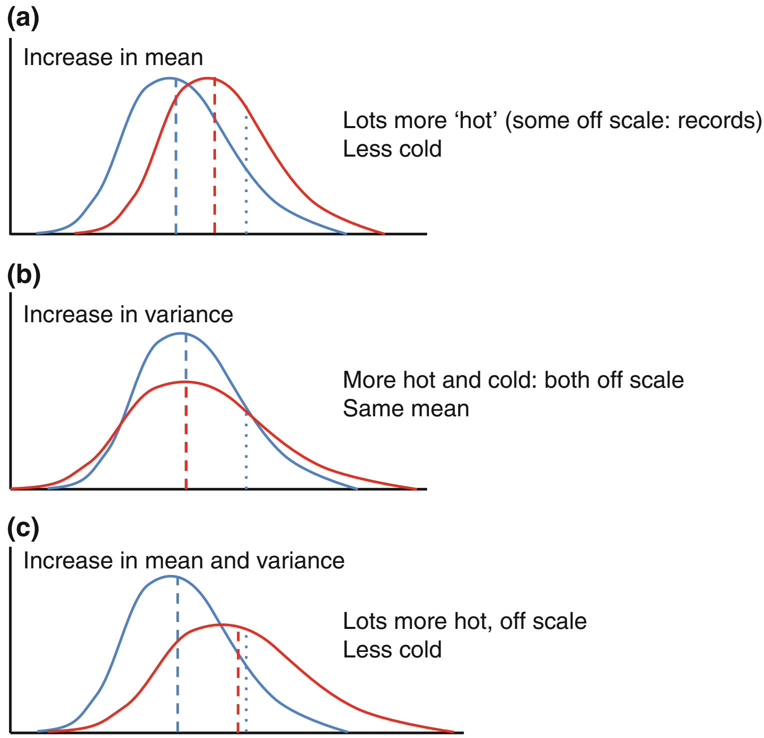

Fig. 3.3 Shifting probability distribution functions are illustrated in different ways going from the *blue* to *red* distribution. The *thick lines* are the distribution, the *thin dashed lines* are the mean of the distributions and the *dotted lines* are fixed points to illustrate probability. Shown is **a** increase in mean, **b** increase in variance (width), **c** increase in mean and variance

precipitation at a given place and time. The extremes (often called the "tails" for their long, skinny graphical appearance) are really the important part. And because they are rare (not very probable; on the graph, a low extent in the vertical), they are hard to predict statistically. Here's a simple example: We often talk about a 50-year flood. This means the flood's "return time" is estimated at 50 years. Or the probability of having such an event in any year is 1/50, or 2 %. If we try to estimate this from a 25- or 50-year record, we may be in error. What if it was a dry period, and in 25 years no floods of a given level were seen? We might conclude that the specific level of flooding can never be higher than what occurred in the last 25 years in a given place. This clearly may not be accurate with a short record. Thus the infrequent tails of the distribution are highly uncertain.

This makes climate change more difficult to estimate. Let's shift the distribution now and assume the climate changes. We can do this first by leaving the shape the same (Fig. 3.3a). Notice what happens to the extremes. At the warm end, the area under the curve beyond some threshold becomes much larger. The area is related to the probability of an event: the fraction of the area is a percent chance of occurrence. And at the cold end, the probability (area) goes way down (gets smaller), even though the mean of the distribution does not change that much.

Here is another example (Fig. 3.3b). Suppose we change the climate by increasing the variability: making the curve wider. The "mean" stays the same, but now the extremes have higher probability in both directions. Here is an example of climate change, without changing the mean (temperature, for example). Think again about living in such a place. Suddenly there is more hot and cold weather, even if the average is the same. In other words, there's a different climate (e.g., more air conditioners or more snow shovels).

Finally, consider a change to both the mean and the distribution (Fig. 3.3c) at the same time. Now one extreme becomes much more probable at the expense of another.

What are the implications? Where does the heat go? When CO_2 is added, the extra heat is absorbed in the atmosphere initially. Recall that it is the heat radiated away from the earth. It's like another thin blanket is added to the thick blankets of greenhouse gases in the atmosphere. The added blanket absorbs a little more heat, which is radiated down to the oceans and land. So there is more energy available at the land surface. There is also more energy available to the ocean surface.

Oceans can warm, but not all the heat added to the ocean will warm the surface temperature. First, some of the heat in the surface ocean may end up in the deep ocean away from the surface. The oceans have a complex circulation, as we will discover in Chap. 6. Some of the water in the ocean is rapidly carried down into the deep ocean in certain regions. If the water contains more heat, this heat will be put deep into the ocean and will not warm the surface. Second, some energy increases evaporation at the ocean's surface and the warmer atmosphere can hold more water. The increased water in the atmosphere can move more heat around. This may not directly heat the surface locally, but it will move heat in the system.

The impacts of these CO_2 changes thus induce several important feedbacks (see box on feedbacks, earlier in this chapter). The first feedback is from additional water vapor that results from warming temperatures. Since water vapor is also a greenhouse gas, adding a little bit of an extra CO_2 blanket to the atmosphere heats the atmosphere by trapping more heat. This allows more water vapor in the atmosphere, which also traps more heat (positive water vapor feedback).

Second, warming due to CO_2 and water vapor may cause changes to the albedo (whiteness) of the planet. This can happen in two ways. Warming can melt snow and ice, or it can change clouds. Melting of snow and ice results in a darker ocean or land surface than when frozen, so more heat is absorbed (a positive snow-albedo feedback). Changes to clouds alter how energy is absorbed or reflected. Clouds are the largest uncertainty in this picture. Clouds broadly cool the planet (they are white and mostly low), but the changes to clouds may warm (if low clouds decrease and the planet is darker) or cool (if the clouds get more extensive).

The resulting changes in the surface temperature and the distribution of heat may change wind patterns. The energy of the water is deposited in different places and changes clouds. The heat going into ice and snow can cause melting when it gets to the melting point. Melting may significantly change the surface albedo. For both clouds and ice/snow, the contrast in color (white ice and clouds versus darker land or ocean) is also important: It causes more energy absorption.

There are several important feedbacks with the terrestrial surface as well. Since plants are made of carbon, they remove it from the atmosphere. Generally, plants get more efficient at growing with more CO_2, just like animals (including humans) do better with more oxygen. If plants have enough water and nutrients to grow, they should increase their growth with more CO_2 in the atmosphere, removing CO_2 into their tissues. This is a negative feedback: More CO_2 enhances its removal by plants. These feedbacks are treated more fully in Chap. 7.

The main point is that increasing CO_2, even a little, throws the earth's climate system out of balance. We have some idea of how it will adjust: There is more heat trapped in this system. This sets off a particular set of feedbacks. Some of the feedbacks are well understood. Some feedbacks are not well understood. Some feedbacks are positive; some are negative. We do not fully know exactly where all the extra energy will show up: as wind, as heat, or as rain. We expect the distribution of climate to evolve over the planet.

3.5 Summary

This chapter has sketched out the essence of climate change. The climate system as a whole responds to a forcing in complex ways. The complexity arises because the different parts of the climate system are coupled together. There are many feedbacks in the system. We have a good idea of the past and present forcing that is pushing on the climate system. For the recent past, we have strong evidence that this forcing is from a buildup of CO_2 in the atmosphere over the past 150 years. From the composition of the atmosphere (isotopes), we know this is a result of human activities: We are changing the very composition of the atmosphere.

Section III of this book will treat in detail the uncertainties in climate prediction, but we can make some broad statements. When discussing future climate change, we usually mean **anthropogenic** (human-caused) climate change, where the change is in response to a forcing from humans. We also can discuss natural climate change. But the human-caused climate change is because of more CO_2, trapping more energy in the system. Globally, the distribution of global average temperatures is expected to shift toward warmer conditions; hence, we sometimes refer to anthropogenic climate change as "global warming." The change in the regional and local distribution of climate variables (temperature and precipitation) might be expected to increase warm extremes at the expense of cold extremes. But the distribution shape may shift over time in ways we do not yet understand. Since different places have different climates with different distributions, they may change in different ways. This might mean big differences in extreme events (the tail of the distributions in Fig. 3.3): tropical cyclones, extended droughts.

We have theories about how the different feedbacks in the climate system work based on observations from past and present climates. We discuss these feedbacks in the context of models in the next chapters. To confirm our understanding, we also try to use models of the system to estimate what has happened in the past and what will happen in the future. We can do this by applying forcing to models and observing how they respond. Thus climate models are used to translate the basic constraints on climate from forcing and feedbacks into specific predictions about regional or local climate changes.

Key Points

- Understanding how parts of the climate system are coupled with feedbacks is critical.
- Greenhouse gases (CO_2) have been increasing over the past 60 years (based on measurements of air samples) and for the past 150 or so (based on ice cores).
- The composition of the atmosphere tells us that the increased CO_2 comes from fossil fuels.
- Increasing greenhouse gases trap more energy in the system. The energy has to go somewhere.